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Lateral Displacement and Shear Lag Effect of Combination of Diagrid-Frame

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Abstract. Diagrid system, which is the portmanteau of diagonal grid member, is an exterior lateral load resisting system for tall building that has gained a wide acceptance in the design of tall buildings. There is abundance of researches that studied the efficiency of diagrid systems, which are constructed from the ground level to the top of the buildings in resisting the lateral load. Nevertheless, no study had been performed on the effectiveness of the diagrid that is constructed above other tall building systems despite the existence of a few buildings in the world that employ such system. The objective of this research is to understand the behavior of the lateral displacement and shear lag effect due to wind load when the diagrid structure is constructed above a frame. Models of 60-story buildings with a footprint of 36m x 36m were analyzed by using Staad.Pro software. The level where the diagrid members started was altered. The lateral displacement was reduced to 60.6 percent and 41 percent of the lateral displacement of a building with full frame system when the combination of frame-diagrid that had the diagrid started at Level 1 and Level 45, respectively were employed. Furthermore, the shear lag ratio was reduced from 1.7 to 1.3 when the level where the diagrid started was increased from Level 1 to Level 45.

1 Introduction

The latest tall building system which now has become favourable among today's designer is diagrid system. Diagrid system is composed of many diagonal structures that connect together to form a triangulated shape or can be seen as grid shape. The term "diagrid" is the combination of "diagonal" and "grid" words, which refers to a structural system that is single-thickness in nature and gains its structural integrity through the use of triangulation [1]. Diagrid structure is different from the braced tube structure as it has no vertical columns present and thus is considered as the evolution of braced tube structure [2]. Diagrid system is favoured due to its structural efficiency and aesthetic potential [3,4]. Diagrid enables the architect to design a building with some unique elements such as irregular angle and nonlinear shape as portrayed in buildings like Swiss Re (30 St. Mary Axe) in London, Capital Gate in Abu Dhabi and CCTV in Beijing. Moon [5] studied the

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structural performance of complex-shaped tall buildings such as twisted, tilted and freeform towers that were designed with diagrid system.

The aesthetically unique design of skyscraper that diagrid provides is mainly due to its free of exterior columns [6]. Since diagrid system allows the elimination of almost all the vertical columns, this system is able to provide variety of open floor plans. Diagrid building is an efficient system because it is able to achieve the same displacement as the displacement of buildings that have other tall building systems with significant reduction of the steel volume. The implementation of diagrid system to Encana Tower that is located in Calgary in Western Canada had reduced approximately 20 percent of the structural steel weight when compared to a building with a conventional moment frame system [7].

Diagrid, which is an exterior structural system, is designed to control the lateral displacement of tall building. The taller the building is the higher the wind load is as wind speed increases parabolically with height from ground. Damage to non-structural elements such as cracking in reinforced walls, damage to lightweight partitions and impaired operation of windows is common examples of the effect of excessive lateral displacement of tall building [8]. Thus, the control of lateral displacement is a serious issue in the design of tall building. A building should not sway horizontally more than H/500 to consider the design criteria that are strength, serviceability, stability and human comfort [9]. American Society of Civil Engineer [10] recommended that the drift limit to be on the order of 1/600 to 1/400 of the building or story height.

Another important issue in the design of high rise building is shear lag. Shear lag is caused by the lack of shear stiffness that reduces the structural effectiveness of the framed tube. In framed tube building, the tube action behaves like a cantilever box beam that is subjected to overturning moment induced by lateral loading, with a significant contribution from the flange elements (the walls that is normal to the direction of the lateral load). The elementary theory of bending that states a plane section remains plane before and after bending can be achieved only when the shear stiffness of the cross section is infinite. Thus, the linear distribution of bending stress in the cross section of the building that results in the same value of axial force in all columns at the flange of the building cannot be achieved in tubular framed building. The axial forces in the columns at the middle of the flange frames lag behind those near the corner and this is called as shear lag effect. The use of diagrid tube structure minimizes the shear lag effect by reducing the difference in the axial force values in the columns at the middle part of the flange with those in the columns at the corner of the flange of the building, as stated by [11] and [12]. However, the increase of the slope of the braces of diagrid increases the shear lag and becomes more rapid when the angle is higher than 70^{o}. Interestingly, shear lag does not correlate with the lateral displacement of high rise building [12].

Full diagrid structures are buildings that have diagrid system being constructed from the ground floor to the top of the building. Most diagrid buildings in the world are full diagrid structures, for example, Swiss Re (30 St. Mary Axe) in London, CCTV in Beijing, United Steelworkers Building in Pittsburgh, USA and Tornado Tower in Doha, Qatar. There are a few buildings in the world that employ combination of diagrid system and other tall building systems at their perimeter, for example, Lotte World Tower in Seoul, Korea which has its diagrid being constructed only from the 107th floor to the top [13] and Hearst building in New York which has its diagrid system being supported by mega columns and super-diagonals that are constructed from the foundation to the 10th floor [14].

Many studies on the performance of full diagrid structures where the diagrid system begins from the ground floor to the top of building have been conducted. However, there is no systematic research that has been carried out on tall building that has diagrid that are constructed above a frame structure. Thus, the objective of this study is to find the effect of constructing a diagrid system above a frame to the lateral displacement and shear lag of a

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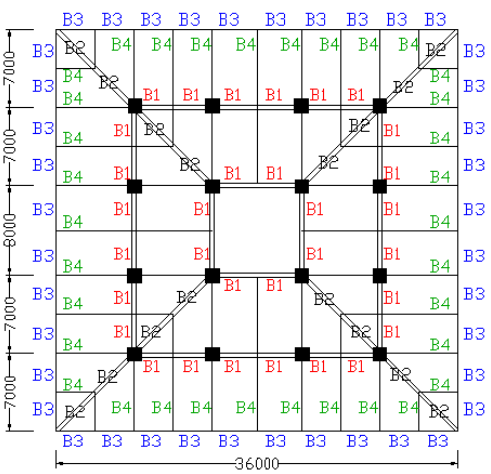
sixty-storey building due to wind load. The story number of the frame that transmitted the force from the diagrid system to the foundation were varied to investigate how they influenced both the lateral displacement and shear lag.

2 Methodology

The structural analysis software, STAAD.Pro V8i was used to analyse all models statically. All elements in the buildings such as beams, columns and diagrid truss were modelled by using line element where each node has three degrees of freedom, which are independent vertical motion, independent horizontal motion and independent rotational motion.

Generally, each model has 60 stories with 4 m storey height and 36 m x 36 m square floor plan as shown in Fig. 1. All columns were reinforced concrete columns. The size of the internal column is 1200 mm x 1200 mm, 900 mm x 900 mm and 600 mm x 600 mm at Level 1 to 20, Level 21 to 40 and Level 41 to 60 respectively. Full diagrid model did not have any external columns, while the models with the combination of frame and diagrid systems did have external columns in the frame system part.



Beam specification :

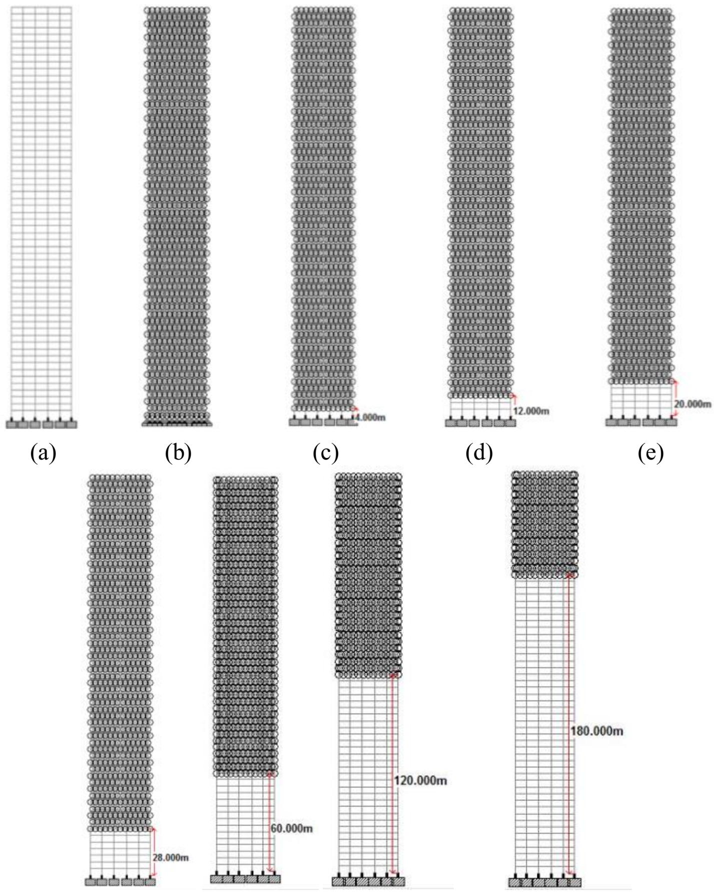
B1 - 650 mm x 250 mm reinforced concrete beam
B2 - 750 mm x 350 mm reinforced concrete beam
B3 - 700 mm x 700 mm x 25 mm thick steel hollow tube
B4 - UB 406x140x53 steel beam

Fig. 1. Typical plan view of all Building Models.

The angle of the triangulated members was uniform and was approximately about 69 degrees, where one module of diagrid was equalled to two storeys of the building. Moon [15] stated that, 69 degrees is the near optimum angle for 60-story high building with diagrid structure. Furthermore, the intersection between the diagonal members was pin-connection so that axial action merely carries the transverse shear and moment. The diagonal members had pinned supports, while the external and internal columns had fixed-end supports. Models of combination of diagrid and frame systems used reinforced concrete beams of 400mm x 1000 mm as the transfer beams that transmitted the axial forces in the diagrid system to the frame system

Model 1 is a frame model without any diagrid while Model 2 is a full diagrid building. For the study of combination of frame and diagrid system, the frame system was at the lower level while diagrid system was at upper level. The level where the diagrid started was varied to Level 1, 3, 5, 7, 15, 30 and 45 as shown in Fig. 2.

The wind load was calculated based on the procedure provided in the ASCE7-10. Two wind environments that were considered are Malaysian wind speed, which is benign and Hong Kong wind speed, which is more aggressive. Determination of the displacement of a building is a serviceability design while the determination of shear lag is a survivability design. Thus, the 3-second gust wind speed for 10-year return period at 10 m high for Malaysian and Hong Kong wind environment which is 28.14 m/s and 42.48 m/s, respectively were applied during the analysis for displacement. Analysis for axial forces which was used to observe shear lag had the 3-second gust wind speed for 50-year return period at 10 m high for Malaysian and Hong Kong wind environment of 33.5 m/s and 57.4 m/s, respectively. The buildings, further, were assumed to be located in an urban area and thus, exposure B as stated in ASCE 7-10 was used.



(a) (b) (c) (d) (e)

(f) (g) (h) (i)

Fig. 2. Side elevation of 60 storey models (a) Model 1: Frame without diagrid, (b) Model 2: Diagrid started at ground level, (c) Model 3: Diagrid started level 1, (d) Model 4: Diagrid started level 3, (e) Model 5: Diagrid started level 5 and (f) Model 6: Diagrid started level 7 (g) Model 7: Diagrid started level 15 (h) Model 8: Diagrid started level 30 (i) Model 9: Diagrid started level 45.

3 Results and Discussions

Results from the dynamic analysis that was performed on all building models show that the lowest natural frequency of all models exceeded 1 Hz. Thus, the buildings are categorized as stiff buildings, and static analysis is sufficient to determine both lateral displacement and stresses of the models, as in accordance with building code in United States of America, ASCE 7-10 [10].

3.1 Lateral Displacement

The graph of lateral displacement of all models at different level is plotted in Fig. 3. Full frame model has the largest lateral displacement under wind load serviceability limit state condition, while full diagrid has the least lateral displacement. The maximum displacement occurred at the top of the building. The maximum displacement of the full frame model was reduced by 66 percent when full diagrid is used. Models with the diagrid constructed at Level 1, 3, 5 and 7 had less percentage of the reduction of the lateral displacement, but the difference is less than 10 percent. Models with the diagrid started at Level 15, reduced the lateral displacement by 50 percent, which is 16 percent less than the full diagrid. The maximum lateral displacement of the models with diagrid started at Level 30 and 45 is about the same where the lateral displacement is reduced by 41 percent when compared to full frame model.

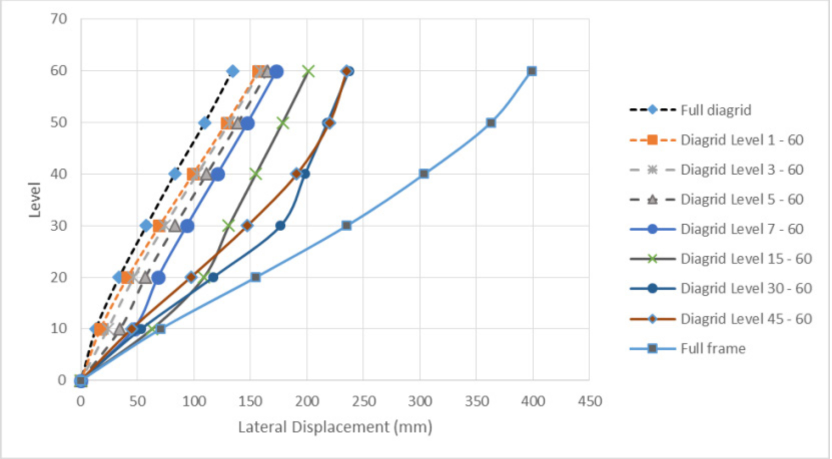


Fig. 3. Lateral displacement of all models in Hong Kong wind environment.

The graph also shows that the interstorey drift became smaller drastically at the level where the diagrid started. Models with diagrid at Level 15-60 has larger interstorey drift from ground level to level 15, but became smaller at level 15 to 60 due to the existence of the diagrid. The same behavior is observed for models with diagrid at Level 30-60 and Level 45-60, where large interstorey drift is observed at lower levels where there was only frame system, but became smaller at the levels where diagrid existed.

3.2 Shear Lag Effect

The axial stress distribution diagram at first storey (z/H = 0.00) of model with full frame system demonstrated the phenomena of positive shear lag where the columns at the edge of flange panel experienced higher axial stresses compared to the middle columns. The lateral load causes compressive axial stresses at the windward face of the building and tensile axial stress at the leeward face of the building. Combining the effect of the weight of the building, results in compressive axial stress at both windward and leeward face of the building where the leeward face has very large compressive axial stress while the windward face has minimal stress. The shear lag effect further, causes the columns at the two corners of the leeward face of the building to have maximum axial stresses while the columns that are located at the middle of the windward face to have minimum axial stresses as depicted in Fig. 4.

Model with full diagrid system had the least value of stresses in both flange and web panel besides being almost uniform (Figure 5). Model 3 which had its diagrid to start at Level 1 had positive shear lag at the first storey (z/H = 0.00), while suffering from the highest stresses at the four sides of the perimeter column, which are 39986 kN and 54240 kN (for Malaysia and Hong Kong wind load case respectively at the building leeward face.

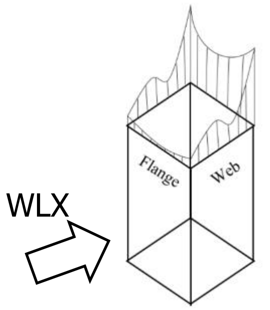


Fig. 4. Axial stress distribution of model with full frame system under wind load.

Furthermore, the axial stress distributions at the ground floor of Model 4, 5, 6, 7, 8 and 9 which are depicted in the graphs in Fig. 5 and Fig. 6, had the same concave up graph shape as Model 3, but lesser value of maximum stresses at the corner columns.

At ground level, the shear lag ratio, which is the ratio of the axial force in corner columns to the axial force in columns at the middle of the panel, increased by 30.8%, which is from 1.3 to 1.7, when one floor high frame is added under the diagrid system. Table 1 shows that the shear lag ratio at the base dropped from 1.57 to 1.26 when the level of where the diagrid started was changed from Level 1 to Level 45. In fact, the shear lag effect is slightly lower than the shear lag of full diagrid, when the diagrid started at Level 45.

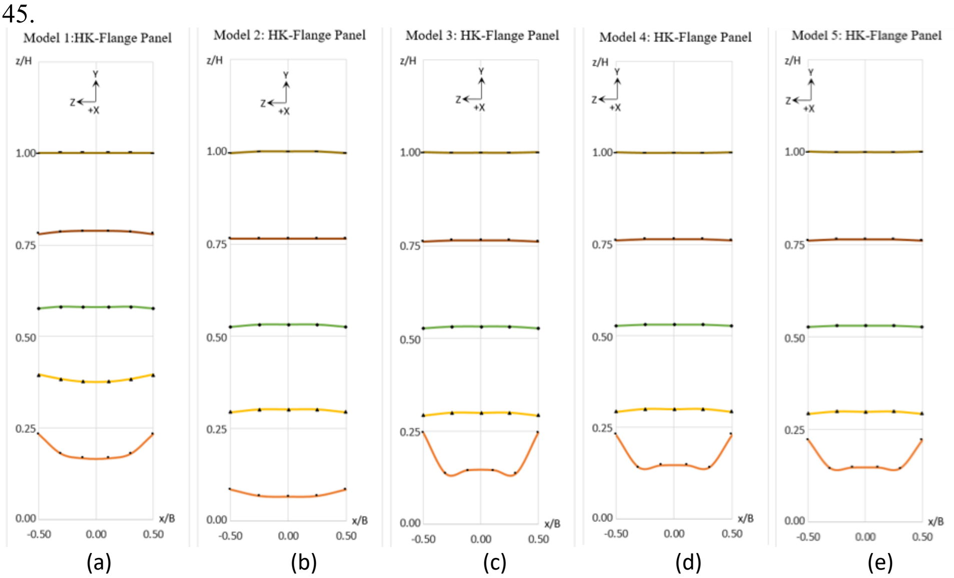


Fig. 5. Axial force distribution at the flange panel of model with (a) full frame (b) full diagrid (c) diagrid at Level 1 – 60 (d) Level 3 – 60 (e) Level 5 – 60.

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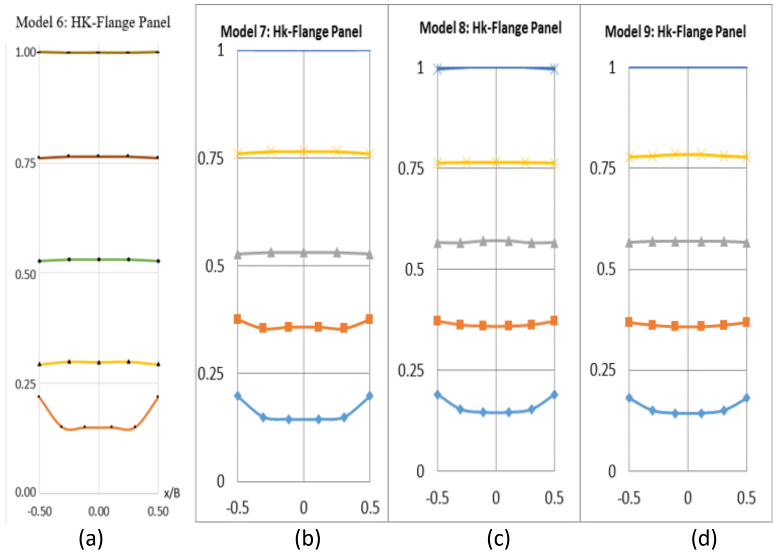

Fig. 6. Axial force distribution at the flange panel of model with diagrid at (a) Level 7 – 60 (b) Level 15 – 60 (c) Level 30 – 60 (d) Level 45 – 60.

In addition, this analysis found that a minor negative shear lag occurred in the region of one-quarter high of the building model from the ground level for full diagrid model and models that have the diagrid started at Level 1, 3, 5 and 7. The models with the diagrid started at Level 15, 30 and 45 did not have negative shear lag at one-quarter high of the model, but had a positive shear lag, instead (Fig. 5 and 6). Negative shear lag phenomena show that the stress at the corners of the flange panel is lower than the stresses at the middle of the flange panel. Furthermore, the stress distribution above one-quarter high of the building model remained the same despite the changes of the level where the diagrid started.

Table 1. Shear lag ratio, *f*, and lateral deflection of all models.

MODEL	HONG KONG WIND LOAD CASE		
	DEFLECTION (mm)	SHEAR LAG RATIO, *f*	
		BASE	MID-HEIGHT
Full Frame	398.696	1.39	0.96
Full diagrid	134.2	1.3	0.79
Diagrid at Level 1-60	157.0	1.7	0.87
Diagrid at Level 3-60	159.0	1.57	0.87
Diagrid at Level 5-60	165.3	1.5	0.87
Diagrid at Level 7-60	173.1	1.46	0.87
Diagrid at Level 15-60	201.329	1.369049	0.88314
Diagrid at Level 30-60	237.092	1.302932	0.946925
Diagrid at Level 45-60	235.266	1.255534	0.964197

4 Conclusions

The study proved that constructing the diagrid above a frame system is still effective in reducing the lateral displacement but not as much as a full diagrid system. The lateral displacement is reduced by 60.6 percent and 41 percent of the lateral displacement of a full frame when the diagrid system is constructed starting from Level 1 and Level 45 of the building respectively.

Shear lag ratio was increased from 1.3 to 1.7 when the diagrid started at Level 1 instead of started at ground level. However, the shear lag ratio was reduced as the higher the level where the diagrid started. As a conclusion, combination of diagrid and frame system is efficient in reducing the lateral displacement but not efficient in reducing the axial force in the external columns.

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